Extragalactic Relativistic Jets and Nuclear Regions in Galaxies

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Summary. Past years have brought an increasingly wider recognition of the ubiquity of relativistic outflows (jets) in galactic nuclei, which has turned jets into an effective tool for investigating the physics of nuclear regions in galaxies. A brief summary is given here of recent results from studies of jets and nuclear regions in several active galaxies with prominent outflows.

1 Introduction

Substantial progress achieved during the past decade in studies of active galactic nuclei (see [25] for a review of recent results) has brought an increasingly wider recognition of the ubiquity of relativistic outflows (jets) in galactic nuclei [5, 43] turning them into an effective probe of nuclear regions in galaxies [21]. Emission properties, dynamics, and evolution of an extragalactic jet are intimately connected to the characteristics of the supermassive black hole, accretion disk and broad-line region in the nucleus of the host galaxy [25]. The jet continuum emission is dominated by non-thermal synchrotron and inverse-Compton radiation [40]. The synchrotron mechanism plays a more prominent role in the radio domain, and the properties of the emitting material can be assessed using the turnover point in the synchrotron spectrum [20], synchrotron self-absorption [19], and free-free absorption in the plasma [12, 42].

High-resolution radio observations access directly the regions where the jets are formed [11], and trace their evolution and interaction with the nuclear environment [30]. Evolution of compact radio emission from several hundreds of extragalactic relativistic jets is now systematically studied with dedicated monitoring programs and large surveys using very long baseline interferometry (such as the 15 GHz VLBA[1] survey [13] and MOJAVE [18]). These studies, combined with optical and X-ray studies, yield arguably the most detailed picture of the galactic nuclei. Presented below is a brief summary of recent

[1] Very Long Baseline Array of National Radio Astronomy Observatory, USA

Table 1. Characteristic scales in the nuclear regions in active galaxies

	l [$R_{\rm g}$]	l_8 [pc]	$\theta_{\rm Gpc}$ [mas]	τ_c [yr]	$\tau_{\rm orb}$ [yr]
Event horizon:	1–2	10^{-5}	5×10^{-6}	0.0001	0.001
Ergosphere:	1–2	10^{-5}	5×10^{-6}	0.0001	0.001
Accretion disk:	10^1–10^3	10^{-4}–10^{-2}	0.005	0.001–0.1	0.2–15
Corona:	10^2–10^3	10^{-3}–10^{-2}	5×10^{-3}	0.01–0.1	0.5–15
Broad line region:	10^2–10^5	10^{-3}–1	0.05	0.01–10	0.5–15000
Molecular torus:	$>10^5$	>1	>0.5	>10	>15000
Narrow line region:	$>10^6$	>10	>5	>100	>500000
Jet formation:	$>10^2$	$>10^{-3}$	$>5\times10^{-4}$	>0.01	>0.5
Jet visible in the radio:	$>10^3$	$>10^{-2}$	>0.005	>0.1	>15

Column designation: l – dimensionless scale in units of the gravitational radius, $G\,M/c^2$; l_8 – corresponding linear scale, for a black hole with a mass of $5\times10^8\,{\rm M}_\odot$; $\theta_{\rm Gpc}$ – corresponding largest angular scale at 1 Gpc distance; τ_c – rest frame light crossing time; $\tau_{\rm orb}$ – rest frame orbital period, for a circular Keplerian orbit. Table is reproduced from [25]

results from studies outlining the relation between jets, supermassive black holes, accretion disks and broad-line regions in prominent active galactic nuclei (AGN).

2 Anatomy of jets

Jets in active galaxies are formed in the immediate vicinity of the central black hole, and they interact with every major constituent of AGN (see Table 1). The jets carry away a fraction of the angular momentum and energy stored in the accretion flow [9] and in the rotation of the central black hole [15, 16, 38]. At distances of $\sim 10^3\,R_{\rm g}$, the jets become visible in the radio regime, which makes high-resolution VLBI observations a tool of choice for probing directly the physical conditions in AGN on such small scales [11, 17]. Recent studies indicate that at 10^3–$10^5\,R_{\rm g}$ ($\lesssim 1\,$pc) the jets are likely to be dominated by pure electromagnetic processes such as Poynting flux [39] or have both MHD and electrodynamic components [29]. The magnetic field is believed to play an important role in accelerating and collimating extragalactic jets on parsec scales [41]. Three distinct regions with different physical mechanisms dominating the observed properties of the jets can be identified: 1) ultracompact jets where collimation and acceleration of the flow occurs; 2) parsec-scale flows dominated by relativistic shocks and 3) large-scale jets where plasma instabilities are dominant.

2.1 Ultracompact jets

Ultracompact jets observed on sub-parsec scales typically show strongly variable but weakly polarized emission (possibly due to limited resolution of the observations). In many cases, the emission is optically thick, indicating that opacity effects may play a prominent role [19]. Ultracompact outflows are probably dominated by electromagnetic processes [29, 39], and they become visible in the radio regime (identified as compact "cores" of jets) at the point where the jet becomes optically thin for radio emission [19, 23]. The ultracompact jets do not appear to have strong shocks [20], and their evolution and variability can be explained by smooth changes in particle density of the flowing plasma, associated with the nuclear flares in the central engine [23]. Compelling evidence exists for acceleration [3] and collimation [11, 17] of the flows on these scales.

2.2 Parsec-scale flows: shocks and instabilities

Parsec-scale outflows are characterized by pronounced curvature of trajectories of superluminal components [13, 23], rapid changes of velocity and flux density and predominantly transverse magnetic field [10]. Relativistic shocks are prominent on these scales, which is manifested by strong polarization [37] and rapid evolution of the turnover frequency of synchrotron emission [26]. Mapping the turnover frequency distribution provides also a sensitive diagnostic of plasma instabilities in relativistic flows [20]. Complex evolution of shocked regions is revealed in observations [7, 10, 23] and numerical simulations [1] of parsec-scale outflows. However, the shocks are shown to dissipate rapidly [23], and shock dominated regions are not likely to extend beyond $\sim 100\,\mathrm{pc}$. Starting from these scales, instabilities (most importantly, Kelvin-Helmholtz instability) determine at large the observed structure and dynamics of extragalactic jets [24, 27, 36]. Non-linear evolution of the instability [33, 34] and stratification of the flow [35] are important for reproducing the observed properties of jets. Similarly to stellar jets, rotation of the flow is expected to be important for extragalactic jets [6], but observational evidence remains very limited on this issue.

3 Jets and nuclear regions in AGN

A number of recent studies have used jets to probe physical conditions in the central regions of AGN. Opacity and absorption in the nuclear regions of AGN have been probed effectively using the non-thermal continuum emission as a background source [21]. The free-free absorption studies indicate the presence of dense, ionized circumnuclear material with $T_\mathrm{e} \approx 10^4\,\mathrm{K}$ distributed within a fraction of parsec from the central nucleus [19, 42].

Absorption due to several atomic and molecular species (most notably due to HI, CO, OH, and HCO^+) has been detected in a number of extragalactic objects. OH absorption has been used to probe the conditions in warm neutral gas [8, 14], and CO and HI absorption were used to study the molecular tori [4, 32] at a linear resolution often smaller than a parsec [30]. These observations have revealed the presence of neutral gas in a molecular torus in NGC 4151 and in a rotating outflow surrounding the relativistic jet in 1946+708 [31].

Connection between accretion disks and relativistic outflows [9] has been explored, using correlations between variability of X-ray emission produced in the inner regions of accretion disks and ejections of relativistic plasma into the flow [28]. The jets can also play a role in the generation of broad emission lines in AGN. The beamed continuum emission from relativistic jet plasma can illuminate atomic material moving in a sub-relativistic outflow from the nucleus, producing broad line emission in a conically shaped region located at a significant distance above the accretion disk [2]. Magnetically confined outflows can also contain information about the dynamic evolution of the central engine, for instance that of a binary black hole system [22]. This approach can be used for explaining, within a single framework, the observed optical variability and kinematics and flux density changes of superluminal features embedded in radio jets.

4 Conclusion

Extragalactic jets are an excellent laboratory for studying physics of relativistic outflows and probing conditions in the central regions of active galaxies. Recent studies of extragalactic jets show that they are formed in the immediate vicinity of central black holes in galaxies and carry away a substantial fraction of the angular momentum and energy stored in the accretion flow and rotation of the black hole. The jets are most likely collimated and accelerated by electromagnetic fields. Relativistic shocks are present in the flows on small scales, but dissipate on scales of $\lesssim 100$ pc. Plasma instabilities dominate the flows on larger scales. Convincing observational evidence exists connecting ejections of material into the flow with instabilities in the inner accretion disks. In radio-loud objects, continuum emission from the jets may also drive broad emission lines generated in sub-relativistic outflows surrounding the jets. Magnetically confined outflows may preserve information about the dynamics state of the central region, allowing detailed investigations of jet precession and binary black hole evolution to be made. This makes studies of extragalactic jets a powerful tool for addressing the general questions of physics and evolution of nuclear activity in galaxies.

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